New Techniques to Test Spin-Gravity Coupling with Atomic Clocks

Lute Maleki
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Recent advances in laser technology have produced the opportunity to realize more stable and accurate atomic clocks, by laser excitation, manipulation and cooling of atoms. In this paper we will describe a new scheme based on the use of lasers with atomic clocks to increase the sensitivity of experimental search for a spin-gravity coupling. There are numerous experiments where atomic clocks have been used to measure the gravitational redshift and search for a violation of the Equivalence Principle. Spin, an inherently quantum mechanical property, is also readily observable in atomic interactions. Thus it is natural to examine the possible coupling of spin and gravity through the observation of atomic resonance experiments, such as with clocks. This class of experiments, however, have been attempted less frequently, primarily because of the high level of control required for parasitic effects that can limit the accuracy of resonance experiments and reduce the sensitivity of measurements. The most recent experiment aimed at a search to place a limit on the strength of the coupling of spin of the electronic and nuclear spin of the atom to gravity was performed in 1992, and was limited by technical noise. The new approach described here eliminates some of the most common sources of uncertainty, without increasing the complexity of the laser excited atomic clocks. This approach can increase the sensitivity of previous tests by several orders of magnitude.

New Techniques to Test Spin-Gravity Coupling with Atomic Clocks

Lute Maleki
Jet Propulsion Laboratory
California Institute of Technology

Outline

- Spin-gravity coupling
- Clock tests
- Laser cooled clocks
- Expected improvements
- Summary

Spin-Gravity Coupling

- Theoretical motivation for coupling of spin and gravity have been made
  - Inertia of spin violates the Equivalence Principle, and CPT
- Particle spin is a fundamentally quantum effect
  - Quantum manifestation of classical gravity

Clock Tests

- Clock tests are extremely sensitive to spin-gravity coupling
  - Time and frequency are the most precisely measurable of all physical quantities
- Previous tests at the level of 10^{-4} Hz
- Limitation of clock tests set by systematic errors due to needed stringent control

$$\omega_0 = 2\pi \, f_0$$

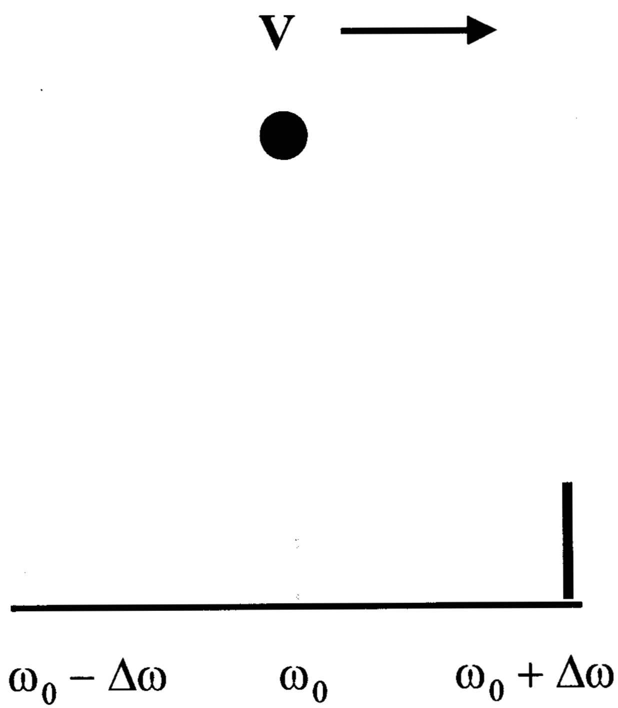
$$Q_1 = \Delta f / f_0$$

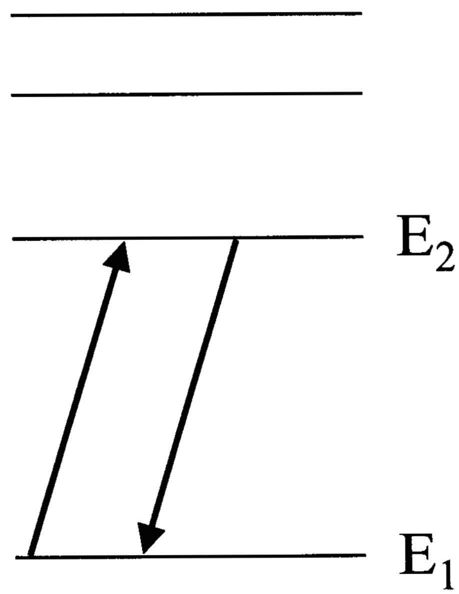
$$\sigma(\tau) = 1/[\, Q_1 \times SNR \times (\tau)^{1/2}]$$

Laser excited Clocks

- Lasers enable exquisite control of atomic excitation
  - Internal degrees of freedom,and external degrees may be controlled
  - Leads to precise population transfer control, and to laser cooling of atoms
- More accurate and stable clocks have been realized based on this

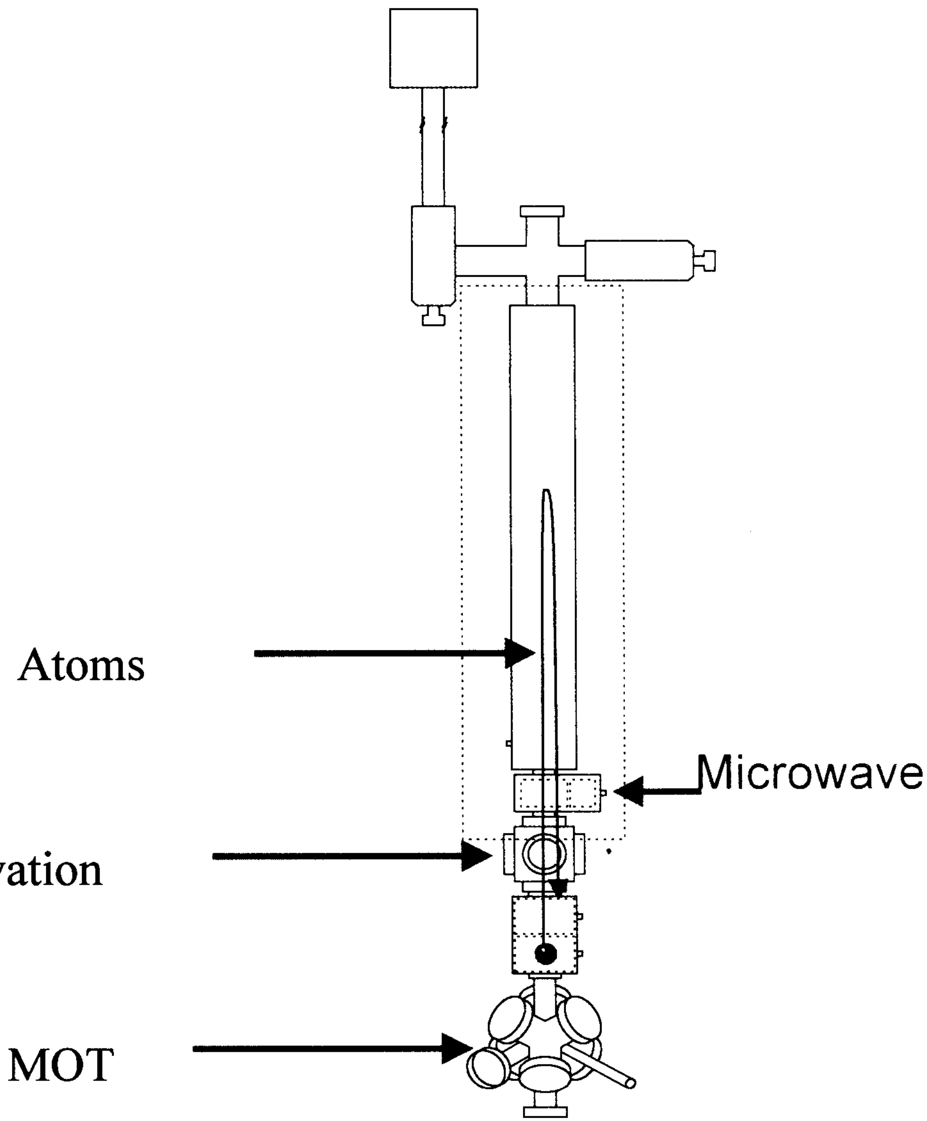
Laser Cooling of Atoms





$$E_2 - E_1 = h(\omega_0/2\pi)$$

Outline of a Fountain



Atomic clocks

- Conventional (microwave) clocks are based on a transition in the ground state hyperfine structure
- Transition is induced by interaction with an applied or a cavity field
- Clocks traditionally operate by inducing transition from $|F,0\rangle$ to $|F',0\rangle$, with $F'>F$

Limitation of tests with clocks

- Previous tests made as absolute measurements
  - Require long measurement times to average down the noise
  - Require control of systematic effects over measurement intervals

Proposed Tests

- Eliminate, or greatly reduce, technical noise by differential measurements:
  - Two clocks in the same environment
  - Both driven by the same fields, thus all limiting systematics are eliminated
  - Key is to compare clocks based on up-down transition with clocks based on down-up transition in the active atom

Example 1

- Laser cooled ytterbium ion clocks
  - Trap with three regions; microwave interrogation region in the middle
  - Ions in the right trap are prepared in the ‘up’ state; ions in the left trap prepared in the ‘down’ state
  - Left and right traps represent two distinct clocks, to be intercompared

Example 2

- Fountain clocks
  - Launch of laser cooled atoms alternate between atoms in the ‘up’ state and atoms in the ‘down’ state
  - Each set of atoms detected by appropriate lasers
  - Each set comprises a separate clock

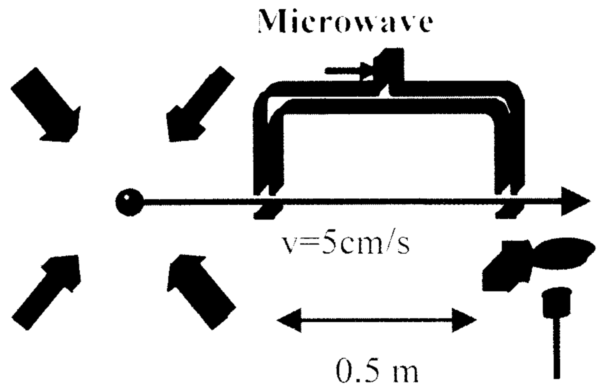
Example 3

- Atom-wave interferometers
  - Acceleration measured by measuring interference fringes of matter waves travelling two different paths
  - Measure acceleration with ‘up’ atoms and ‘down’ atoms and compare
  - Can integrate for many months

Summary

- New technique requires little additional modification to existing clocks, and laser systems
- Eliminates systematics, including that due to the need to change the direction of magnetic fields
- Allows long time integration to average the white noise down
- Can lead to four orders of magnitude improvement, and more to gain if done in space

Laser Cooled Cavity Clocks



Repeat every 10 s →

$$\sigma_y(\tau) = \frac{\Delta\upsilon}{\pi\upsilon\,\mathrm{S/N}}\sqrt{\frac{T}{\tau}} = 7.3\times10^{-15}\Big/\sqrt{\tau}$$